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Feasibility Study of Magnetic NDE by Impedance Measurement using Single-yoke

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Abstract

This work is a feasibility study of nondestructive evaluation (NDE) for degradation in installed structural components by impedance measurement. Inductance and resistance of a single-yoke coil located on cold-rolled plates and deformed ones were investigated. Impedance decreases with increasing the reduction ratio for the cold-rolled plates, whereas it is nearly constant in elastic region and decreases with increasing the tensile stress in plastic region for the deformed plates. Additionally, the single-yoke scanned the wider surface of the deformed plates and the impedance distribution of the deformed steels was evaluated. Impedance distribution will reflect the distribution of mechanical properties of the deformed steels. This shows potential of magnetic NDE for structural components using impedance measurement of the single-yoke.

Keywords: single-yoke, permeability, nondestructive evaluation, impedance

1. Introduction

Since microstructures of structural steels have strongly influences on both their mechanical and magnetic properties, magnetic properties are well correlated with mechanical properties[1], [2]. Potential of nondestructive evaluation (NDE) of mechanical properties or degradation of structural steels using magnetic measurement has therefore been proposed. In order to apply magnetic method using parameters obtained from hysteresis magnetization curve and barkhausen noise for practical uses, many fundamental researches have been accomplished[3]-[8]. However those techniques require a large applied field to saturate specimens magnetically. Thus, they are not suitable for actual use in a wider range and with a low consumption energy. Ac permeability is a more useful parameter than one obtained from a hysteresis curve from the viewpoints of low electricity consumption and real-time measurement, because it can be detected by applying small field excitation and higher frequency compared with hysteresis measurement.

We examined a possibility of NDE using ac permeability and clarified that ac permeability has a good correlation with mechanical properties using ring-shaped or frame-shaped samples made from iron, Fe-Cu alloy and low carbon steels[9]-[11]. However it was not NDE because machining samples was required. In this study, so as to apply a magnetic method using ac permeability to NDE technique, a single-yoke made of soft ferromagnetic steel was adopted, and impedance of a coil wound on the single-yoke was evaluated. Impedance is proportional to permeability of specimens, and permeability reflects the changes of mechanical properties, consequently, NDE using impedance measurement will be possible. Moreover, the single-yoke scanned the overall surface of large specimens and the distribution of mechanical properties was assessed.

2. Experimental Procedure

Low carbon steel, S15C, and structural steel, SM490A, were prepared in this study. The chemical compositions of both steels are listed in Table 1. S15C steels were cold-rolled with the reduction ratios of 0, 5, 10, 20 and 40 %, and SM490A steels were elastically and plastically deformed with the tensile stresses of 0, 288, 457 and 518 MPa. The dimension of the plates obtained from each steels are illustrated in Fig. 1.

A magnetic single-yoke, made of Fe-Si steel, having a winding coil was adopted in order to measure impedance of the coil. The single-yoke was located on the center of the plates and a closed magnetic circuit was composed as shown in Fig. 2, where the dimension and the configuration of the single-yoke are also shown. An impedance of the coil wound around a leg of the single-yoke was measured using LCR meter (HIOKI 2250) with frequency range from 1 Hz to 1 kHz. Here the impedance Z, inductance L and resistance R, of the coil are the functions of initial permeability, μ_i, of the steels. The relation between Z, R and L is expressed by $Z = R + j2\pi fL$, where f is frequency. When

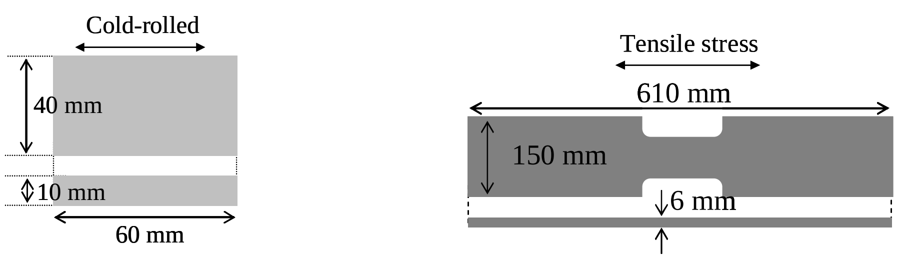
Table 1 Chemical compositions of the steel (wt. %).

(a) S15C

C	Si	Mn	P	S	Fe
0.018	0.04	1.19	0.013	0.005	bal.

(b) SM490A

C	Si	Mn	Fe
0.15-0.20	0.15-0.35	0.30-0.60	bal.



(a) S15C (b) SM490A

Fig. 1 The dimension of the plates.

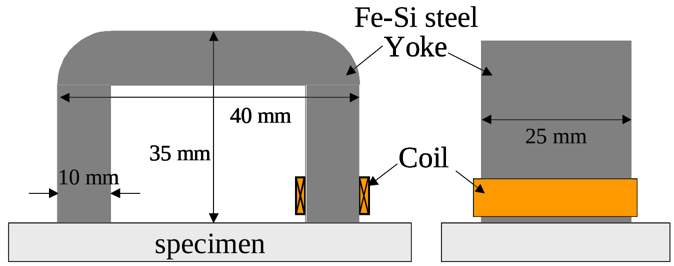


Fig. 2 The dimension and the configuration of the single-yoke.

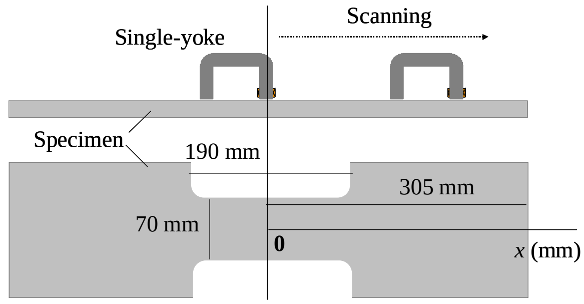
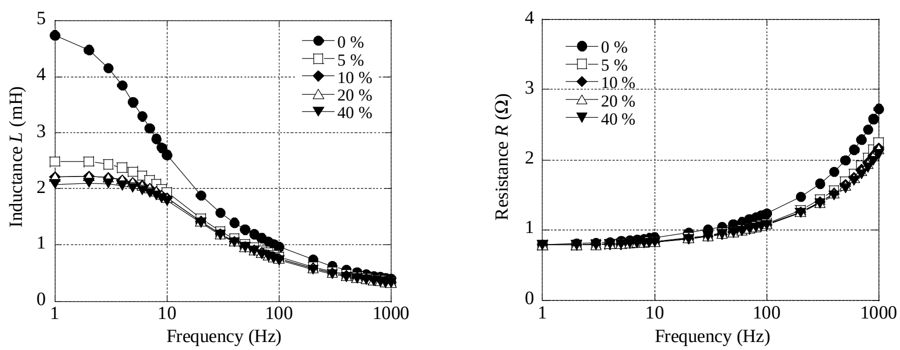
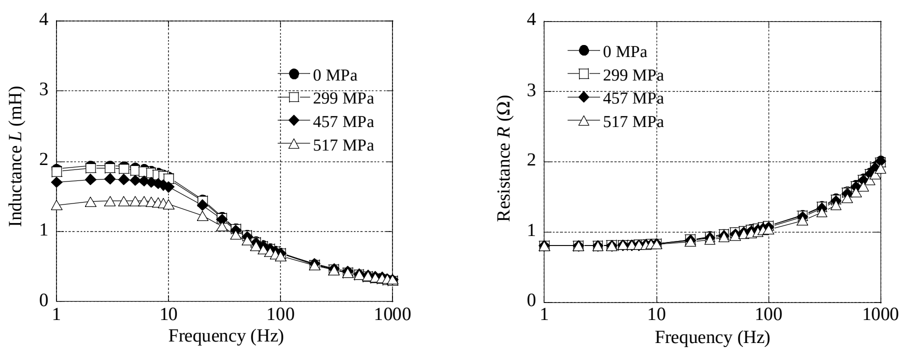


Fig. 3 Explanation for scanning the single-yoke over the SM490A plates.



(a) Inductance (b) Resistance

Fig. 4 Frequency dependence of impedance for S15C steel.



(a) Inductance (b) Resistance

Fig. 5 Frequency dependence of impedance for SM490A steel.

measuring impedance, an ac current of 10 mA was applied to the coil wound around the single-yoke leg and applied to magnetize plates in parallel to the direction of cold-rolled and tensile stress.

For SM490A steel plates, the single-yoke scanned over the specimens in x direction; i.e., in parallel to the length direction of the plates, as shown in Fig. 3 and impedance distribution was evaluated. Here, the center of the plates is defined as $x = 0$.

Vickers hardness of S15C steels were also evaluated by a hardness meter with a load of 500 g.

3. Results and Discussion

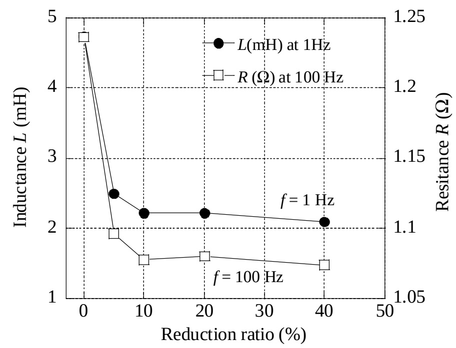


Fig. 6 Relation between impedance and the reduction ratio for S15C steel.

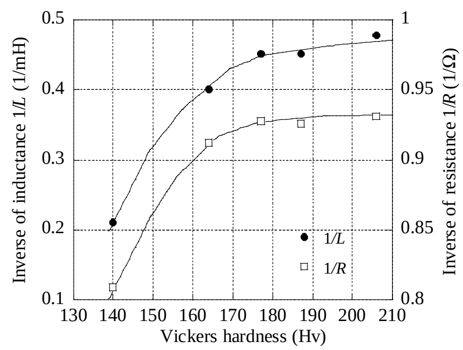


Fig. 7 Relation between impedance and Vickers hardness for S15C steel.

Fig. 4 and Fig. 5 show the frequency dependence of the impedance measured by the single-yoke for S15C steels and SM490A steels, respectively. Inductance is almost constant at low frequency region, except the case of S15C steel with the reduction rate of 0%, and then decreases with the increase of frequency due to eddy current loss, whereas resistance is also constant up to 10 Hz, followed by its increase with upward frequency. Inductance at low frequency region decreases with increasing the reduction ratio for S15C steels, and with increasing the tensile stress for SM490A steels. Inductance at higher frequency region has no significant changes when the reduction ratio or the tensile stress changes. Resistance at low frequency region is almost same values even if the reduction ratio or the tensile stress changes. On the other hand, resistance at higher frequency decreases with increasing the reduction ratio for S15C steels, and with increasing the tensile stress for SM490A steels.

Fig. 6 shows the changes in inductance at 1 Hz and resistance at 100 Hz, against the reduction ratio for S15C steels. Both values decrease with increasing the reduction ratio. It is due to the increase of dislocation density of the steels. Dislocations act as the pinning sites for domain wall motion, which introduces the reduction of permeability in the steels, and inductance is proportional to permeability. Resistance increases due to joule heating by eddy current at higher frequency, and eddy current is a function of permeability.

The relation between Vickers hardness and the inverse of inductance at 1 Hz, resistance at 100 Hz for S15C steel, are shown in Fig. 7. One can see that there are good correlations between impedance and Vickers hardness; this indicates it is possible to evaluate mechanical properties, such as Vickers hardness, by impedance measurement.

Fig. 8 shows the changes in inductance at 1 Hz and resistance at 100 Hz against the tensile stress for SM490A steel. Both values are constant up to 299 MPa, and then decrease as the tensile stress increases. The yield stress of SM490A steel is 457 MPa; this

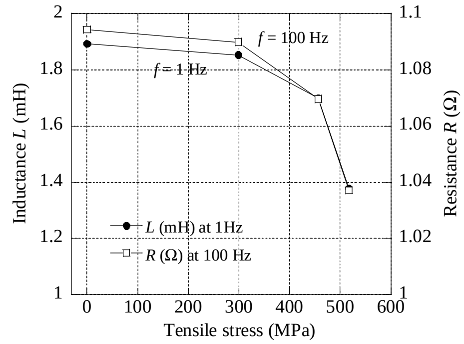
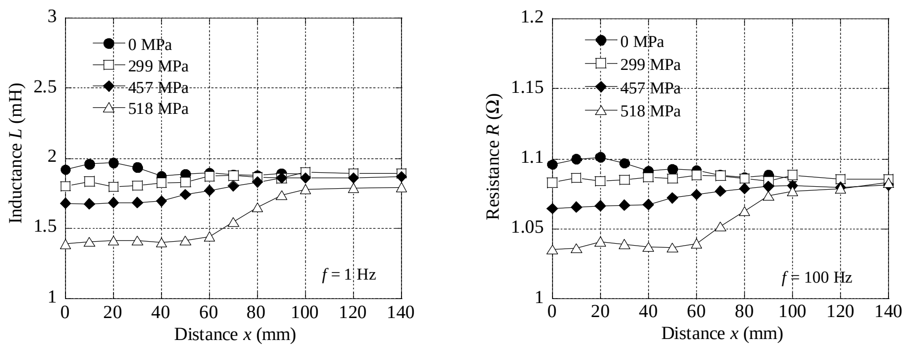


Fig. 8 Tensile stress dependence of impedance for SM490A steel.



(a) Inductance (b) Resistance

Fig. 9 Spatial distribution of impedance for SM490A steel.

means 0 and 299 MPa are elastic region, thus, impedance did not change significantly in that region. However, applying tensile stress of 457 and 518 MPa, at which stress is above the yield stress, introduce plastic deformation in the steels, consequently, dislocations increase in the specimens. Impedance, inductance and resistance, decreases in this region due to the same mechanism mentioned in the results for S15C steel.

Fig. 9 shows the results of inductance (at 1 Hz) and resistance (at 100 Hz) changes when the single-yoke scanned the deformed plates of SM490A steel. Inductance and resistance are almost constant in all areas of the plates with 0 and 299 MPa stressed, whereas they distribute in the plates with 457 and 518 MPa. Inductance is nearly 1.68 mH and resistance is about 1.06 Ω in area of x = 0 to 40 mm for the plate with 457 MPa, and those values increases gradually in x = 40 to 100 mm. Beyond the distance of 100 mm, those values correspond with the values of elastic region: L = 1.80 mH and R = 1.08 Ω. This means that specimens are not deformed in this area. In case of the plate with 518 MPa, impedance is constant up to 60 mm: L = 1.40 mH and R = 1.03 Ω, and then, increases in the area of 60 -100 mm, and finally reached to the values of elastic region. These results show that the center of the specimens deformed more and its deformation area spreads gradually, with increasing the tensile stress applied to the specimens.

4. Conclusion

A single-yoke was adpted to examine the potential of NDE using impedance measurement for low carbon and stractural steels. Inductance at low frequency and resistance relatively higher frequency has good correlation with hardness of S15C and applied tensile stress of SM490A steel. Scanning of the large plates of SM490A steel using single-yoke was demonstrated and the evaluation of the distribution of impedance, reflects the distribution of mechanical properties, was successfully performed. These results show the feasibility of NDE for the stracural component composed of ferromagnetic steels by impedance measurement using single-yoke with wider range scanning and real-time measurement.

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